Selenium Hexafluoride with ^{82}Se as a candidate for 0-ν ββ search

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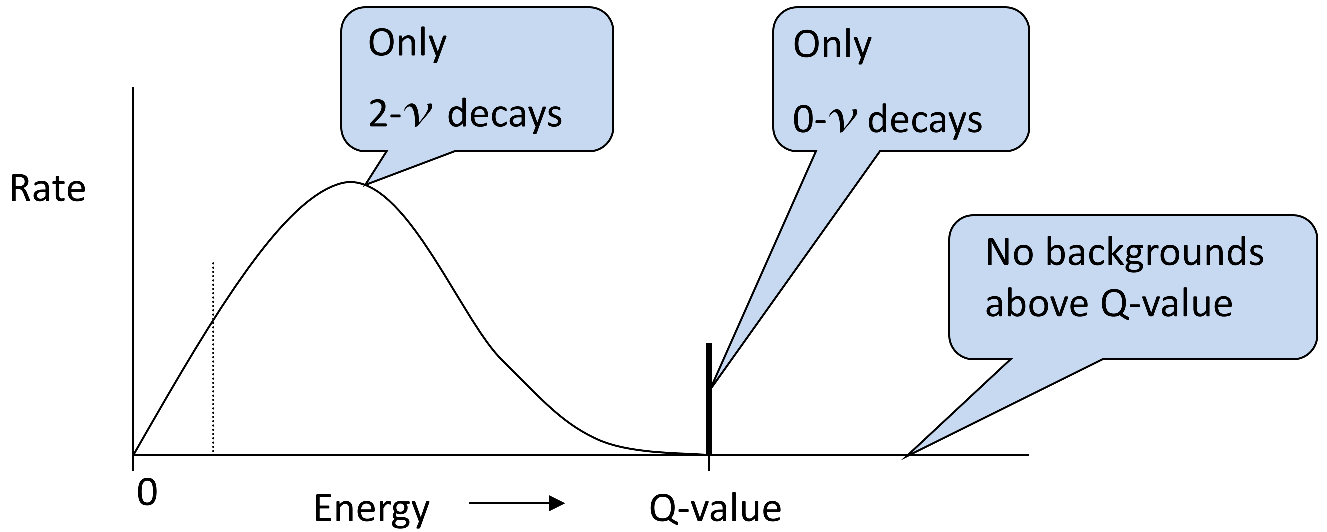
Double beta decay – ideal result



The ideal result is a spectrum of all ββ events, with a 0-ν signal present as a narrow peak, well-separated from 2-ν

Criterion for 0ν-ββ discovery

- A Background-Free positive result
  - Signal present at exact Q-value energy
  - No contamination of ROI and in side-bands
  - No expectation of contamination in simulation
  - Background level for 3% probability per ton/year:

→ 3 x 10^{-5} ct/kg/year (1% FWHM resolution), or

1 x 10^{-6} ct/kev/kg/year

This has never been achieved!

Second criterion for 0ν-ββ discovery

- Replacement of enriched isotope target mass with depleted isotope mass – gives no signal

  – Positive signal disappears with depleted isotope;
  – No other change to system is necessary;
  – Only gas/liquid target mass can do this easily;
  – Background-free allows result in human lifetime.

Some candidate isotopes

Isotope	$G^{0\nu}$ (10^{-14} y^{-1})	$Q_{\beta\beta}$ (keV)	Nat. ab. (%)
^{48}Ca	6.35	4273.7	0.187
^{76}Ge	0.623	2039.1	7.8
^{82}Se	2.70	2995.5	9.2
^{96}Zr	5.63	3347.7	2.8
^{100}Mo	4.36	3035.0	9.6
^{110}Pd	1.40	2004.0	11.8
^{116}Cd	4.62	2809.1	7.6
^{124}Sn	2.55	2287.7	5.6
^{130}Te	4.09	2530.3	34.5
^{136}Xe	4.31	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

Gamma-ray backgrounds

- A sharp drop in γ-ray backgrounds occurs above the ^{208}Tl (2615 keV) line

- The Q-value of ^{82}Se: 2.995 MeV

- A very attractive candidate for gas phase

We have to use <u>all</u> information

- There are two electrons in the decay
- The electrons emanate from some point (the parent nucleus) along a continuous track
- Energy is given entirely to decay electrons
- There are no other confounding energy depositions near the event in time and space
- The event occurs entirely within active volume
- The daughter atom can be identified

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We have to visualize the event

- This may mean a gaseous detector
  - Total active isotope may need to reach 1 ton
- GERDA and CUORE may yet claim a positive result
  - Very expensive to enrich germanium, tellurium
- Length of tracks in xenon at 10 bars is ~15 cm
  - Z = 54; Multiple scattering in xenon is large
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- What other gaseous material can we use?
  - How about selenium hexafluoride – SeF_6 ?

Some Properties of SeF_6

- Remains a gas up to several bars
- Used in early days of HV electrical insulation
- Replaced by SF_6 due to toxicity to humans
- Easy to enrich to $^{82}SeF_6$ (9% nat. abundance)
- Highly electronegative - no free electrons
- Good dielectric strength – “no sparks”

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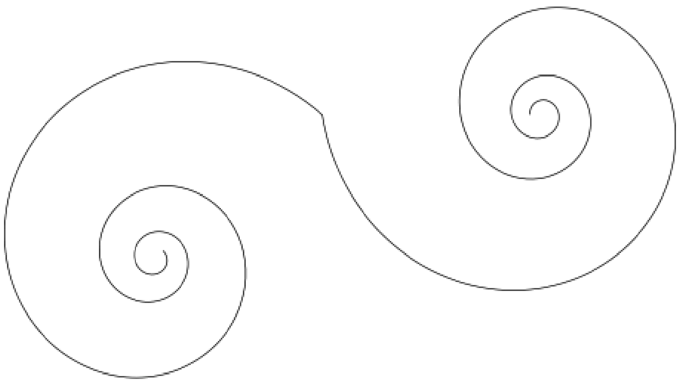
- Cannot sustain well-behaved avalanche gain.

Two electrons from a common point: The "Golden Dingbat" signature



Two electrons that emerge from a common point in a magnetic field yield this generic pattern.

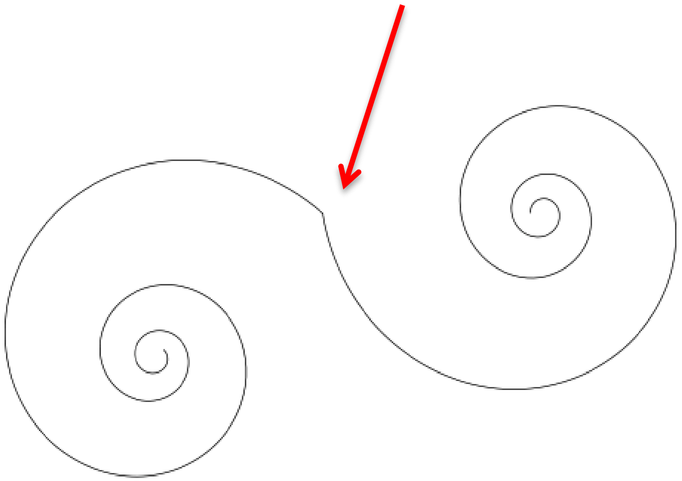
Pair production gives a V or rams-horn pattern, recognizably different

Multiple scattering is not included in this artistic impression!

Issue: what is the magnetic field required to provide clear two-electron recognition for this signature? Where does one start?

Curvature integrals

Find the point along the continuous combined track that maximizes the curvature integrals characteristic of two electrons emerging from the nucleus.



SeF_6

- Average Z is much smaller than that of xenon

  (6 x9 + 32)/7 ≈ 12, compare with Z = 54
- But 7x more scattering centers per molecule

  Could add a lot of low Z gas, but complicated
- What is the efficiency for recognizing the two-electron topology by magnetic curvature?

  Needs careful simulation,

  Not yet done...

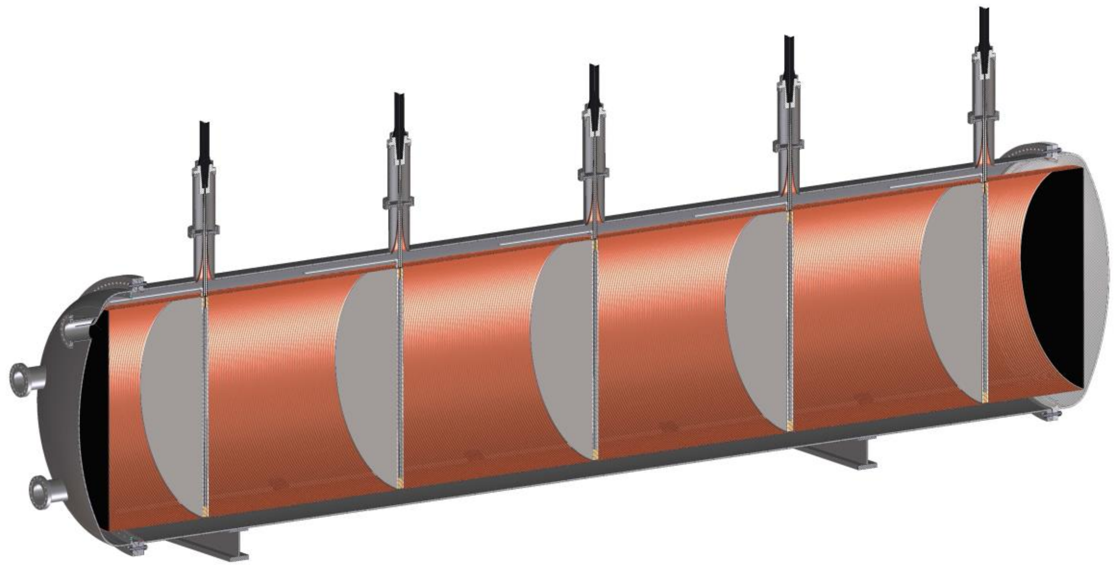
Algorithmic Challenges

- Ferret out the continuous, relentless, small deflections in x-y due to the magnetic field.
- Identify and nullify large point-like deflections due to MCS that occur in x-y-z.
- What quality of tracking is needed to do this?

Technical challenges

- How does read out a track without avalanche or electroluminescent gain?
- The electrons are quickly captured, leading to a negative ion image – this may be a bit blurry
- Positive and negative event “images” move in opposite directions in a TPC.
- The event images carry identical information!
- **Solution: read out both – with no gas gain!**

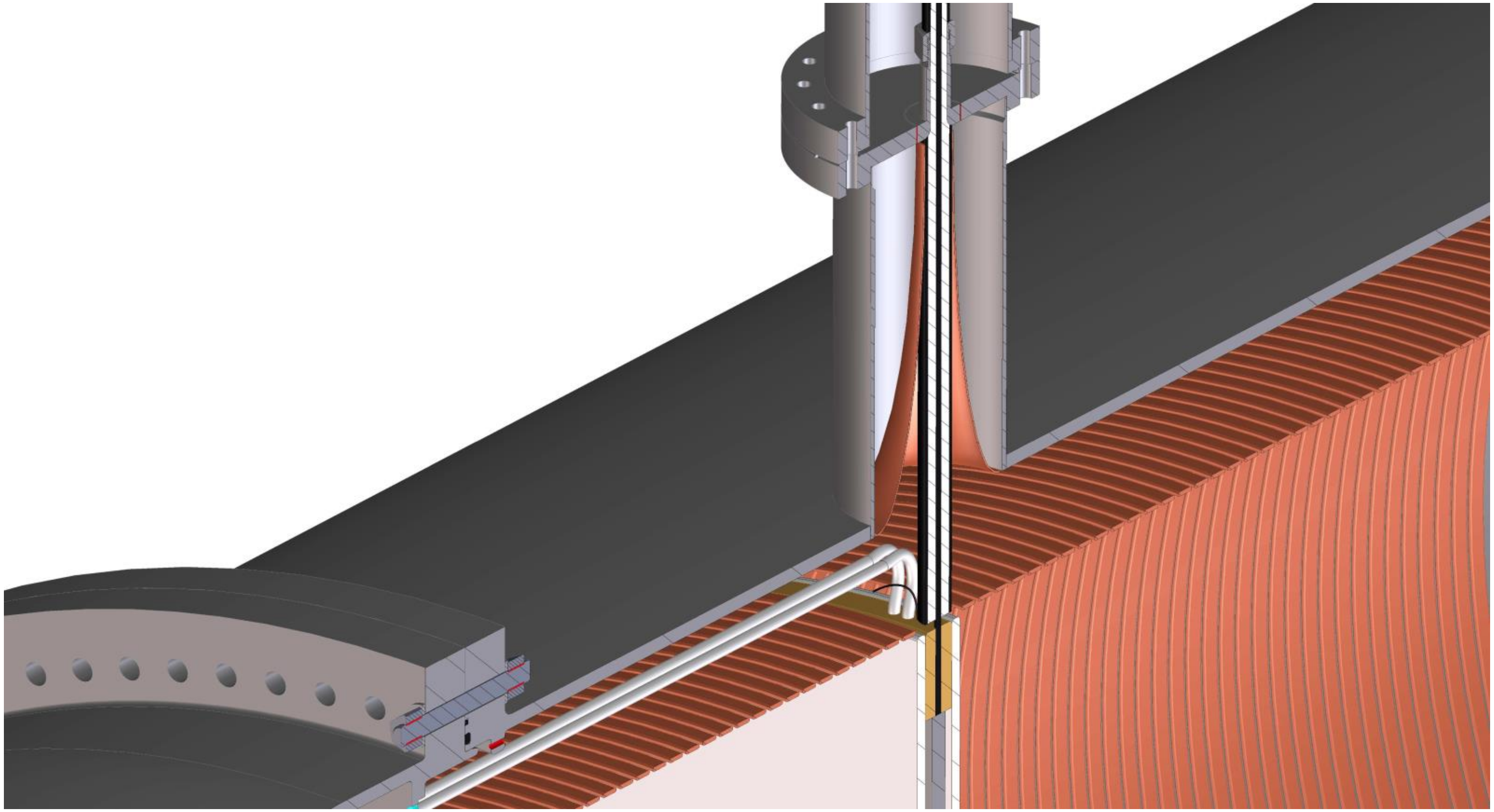
Tank-Car Model



Alternating anode and cathode assemblies capture positive and negative track images
Unpleasant end effects are manageable

The detector is a cascade of symmetric TPCs, with readout planes operating at ±HV. Each TPC segment supports a drift length of about 1 meter. Ultra-sensitive electronics for tracking and energy measurement are contained within the readout planes, which are active on both sides. Power for the electronics is brought in at HV, similar to the way x-ray tube filaments are powered by a single two-wire insulated cable.

Study of HV penetration and fiber



Track images

- Track images drift slowly, at perhaps <1 mm/ms
- Ionic diffusion is low, ~ 1 mm rms/m
- No trigger possible
- Record all non-zero data with time-stamps
- Must record and match both positive and negative images to place an event in space.
- Two images improve energy resolution by $\sqrt{2}$

What is the tracking function?

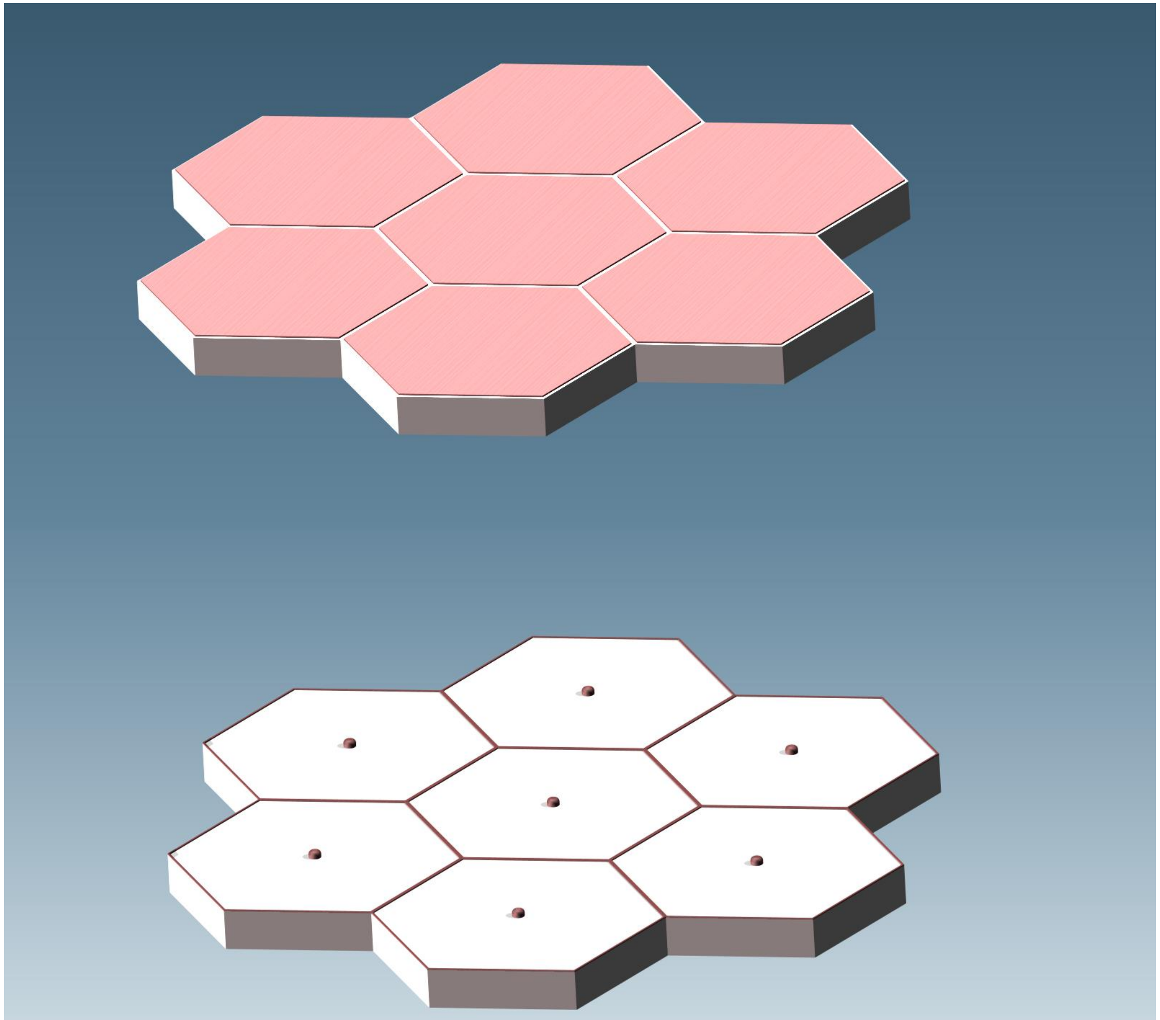
- **"Direct Ionization imaging"**
  - No gas gain
  - Ultra-low capacitance pixels
  - Ultra-low noise electronic system: ≈10 e^- rms
  - Gated integrator architecture
  - Correlated multiple sampling at ~1 MHz
  - Front-end reset transistor "off" for 500 μs
  - Dead-time ~ 1% - a manageable correction

One electron present, or two?

- For curvature measurement, how many samples?
- Assume 60 – 100 spatial points
- Assume 6 samples in time for each space point.
- 360 – 600 samples → 480 average # samples
- Start in middle of track, or at large kink
- Build curvature integrals to both ends of track
- Find starting point that maximizes integrals
- Both integrals have to exceed threshold

Energy resolution

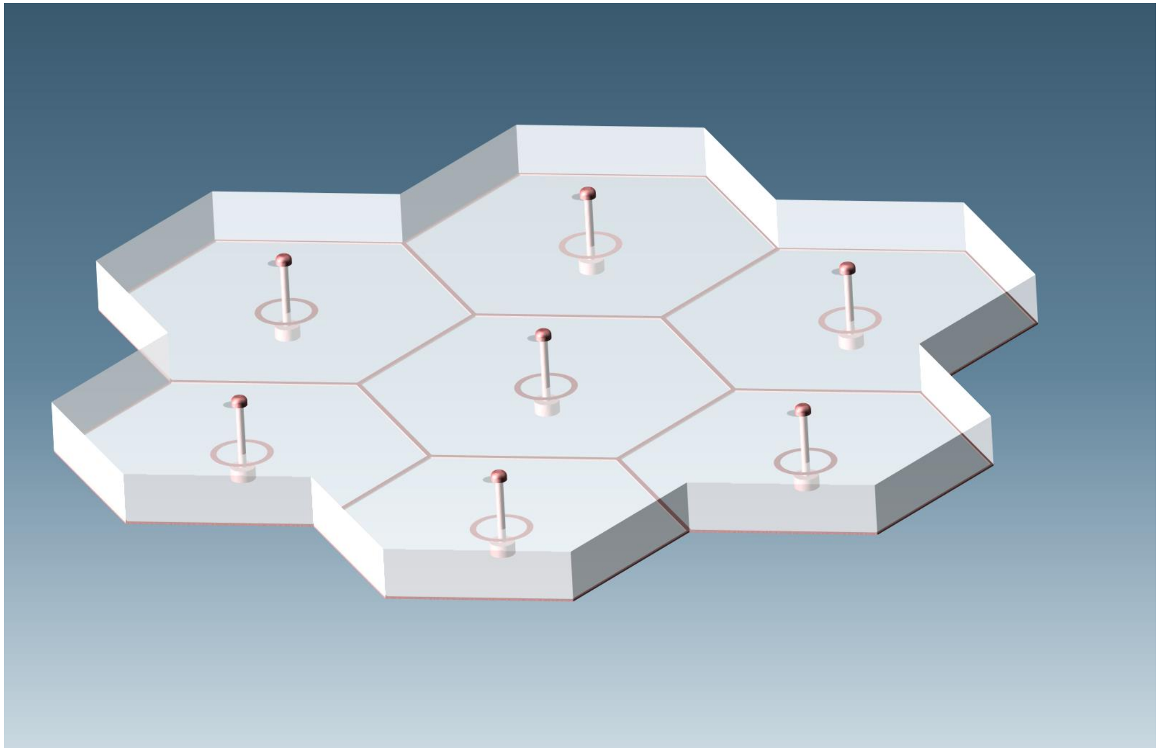
- Impose 1% FWHM energy resolution/ image
- For 3000 keV, w = 25 eV, N = 120,000 ions x2
- Total noise budget is 510 electrons (ions)
- Intrinsic fluctuation for F = 0.15 = 134 e^- (ions)
- Electronic noise budget is 480 electrons (ions)
- 480 samples → ≤ 22 e^- rms noise per sample
- This noise level *may* be possible



Two pixel plane designs. The top has simple copper pads connected by vias to the circuits behind. The size of each pixel is about 3 x 3 mm^2

The bottom pixel plane has much lower capacitance and less cross-talk - much better than the top design. But charges can creep from the lacework to the sensing point…

“Hidden grid”



In this illustration, the viewer is looking down through dielectric (transparent here for clarity). A small copper button is the only metallic electrode presented to the charge arriving from the drift region. The grid has been placed on the underside and a small circular guard ring has been added to capture surface currents that would, if allowed to reach the electrode, increase noise.

NEMO is an important example

- **Nemo** measured both electrons emerging from a foil to impose a double-beta signature
  - Magnetic signature from enriched foils
  - Energy resolution was not ideal: 8% FWHM
  - Backgrounds from external gamma-rays were estimated to be < 1 x 10^{-3} within energy ROI
- I estimate that irreducible two-electron backgrounds from external gamma-rays will be ~500 times less in gas phase than in foils.

More..

- With 1% energy resolution instead of 8%, the rejection factor improvement might be ~4000.
- Then backgrounds might be:

2.5×10^{-7} ct/kg/y

A ten-year ton-scale experiment would still have less than 0.3% background count.

Very crude, but still…

What’s not to like?

- Do the ions have unique mobilities?
  - Smearing by clustering would ruin track sensing
- What happens when positive and negative track images cross during drift?
  - Recombination might “cut” the tracks
- Pressurized toxic gas underground reminds us of the disaster of Bhopal – !
  - Immersion in a water tank with neutralizer…?

What’s to like?

- Well, maybe this scheme could deliver a background-free positive result at ton-scale
- Interesting realization of super-low noise tracking could be very stable with no gas gain
- Hidden Grid pixels have lowest possible capacitance → lowest electronic noise
- Super-heroic measures to obtain radiopurity in materials may be less important here
- It’s novel, and may lead somewhere…

Perspective

- By operating in gas phase, it is very unlikely for a gamma-ray to generate two energetic electrons within few mm proximity.
- Residence time of beta-gamma emitters in gas phase is very short.
- Although this approach has several known unknowns, a background-free experiment (in addition to ^{136}Xe!) may be possible…

Thank you